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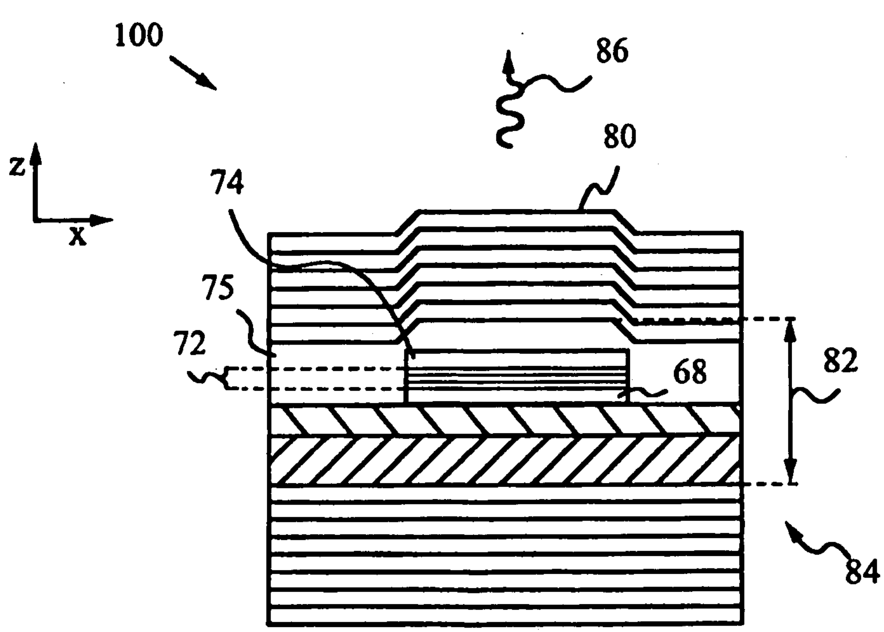
(54) Title: VERTICAL OPTICAL CAVITIES PRODUCED WITH SELECTIVE AREA EPITAXY



(57) Abstract

A monolithic vertical optical cavity device (100) has a bottom Distributed Bragg Reflector (DBR), a quantum well (QW) region consisting of at least one active layer grown on top of the bottom DBR by using a Selective Area Epitaxy (SAE) mask such that the active layer or layers exhibit a variation in at least one physical parameter in a horizontal plane perpendicular to the vertical direction and a top DBR deposited on top of the QW region (70). The device has a variable Fabry-Perot distance (82) defined along the vertical direction

Vertical Optical Cavities Produced with Selective Area Epitaxy

CROSS-REFERENCE TO RELATED APPLICATION(S)

This applications claims priority from the US application 09/050/657 filed March 30, 1998 which is hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to vertical optical cavity structures such as vertical cavity surface emitting lasers (VCSELs) and detectors (VCDETs) grown with the aid of Selective Area Epitaxy (SAE), and especially to arrays of such structures.

BACKGROUND

When metal-organic chemical vapor deposition (MOCVD) is used as the epitaxy technique to grow an epitaxial layer (e.g., InGaAs) on a substrate with patterned windows of silicon dioxide or silicon nitride, the local growth rate on the substrate is enhanced. This is generally referred to as Selective Area Epitaxy (SAE). The reason for the enhancement is due to the fact that growth on top of the oxide or nitride region is inhibited. Thus, the extra material (e.g., tri-ethyl-Gallium and tri-methyl-Indium) migrate towards the uncovered region, enhancing the local growth rate. The enhancement factor depends on the ratio of oxide (nitride) area to the available growth area and the diffusion coefficient of the metal-organic sources.

Previous applications of SAE have all been towards edge emitting lasers and integrated optoelectronic devices. For example, in U.S. Patent No. 5,659,640 issued to Joyner the inventor teaches the use of SAE for making an integrated waveguide with an optical grating. Suitable mask geometry is chosen to ensure that the

deposition process produces the desired optical structure, i.e., an optical grating or even a stack of Quantum Well regions (QWs). In U.S. Patent No. 5,418,183 Joyner et al. teach the use of SAE for producing a reflective digitally tunable laser. Another type of multiple QW distributed feedback semiconductor laser grown with the aid of SAE is taught by Shim et al. in U.S. Patent No. 5,614,436. Additional references illustrating the use of SAE for simultaneously growing optical devices in the same plane are found in the articles of Joyner et al., "Extremely Large Band Gap Shifts for MQW Structures by Selective Epitaxy on SiO_2 Masked Substrates," IEEE Phot. Tech. Lett., Vol. 4, No. 9 (Sept. 1992), pp. 1006-9 and Caneau et al., "Selective Organometallic Vapor Phase Epitaxy of Ga and In Compounds: A Comparison of TMIn and TEGa versus TMIn and TMGa," J. Crystal Growth, Vol. 132 (1993), pp. 364-370.

These and similar prior art devices typically have InGaAs QWs in their active region. These QWs are regrown on a patterned substrate with different openings between two oxide strips. The thickness of the QW is inversely proportional to the oxide strip opening due to SAE. Moreover, since the SAE enhancement factor for In is more than the Ga enhancement factor, the In content of the QW is also a function of the oxide strip opening. Hence, the emission wavelength of each laser in the array can be tailored by the oxide strip opening.

The optical elements of the prior art devices are all located in the plane in which SAE is performed. In other words, SAE is performed on a surface which provides for planar alignment between the optical elements. Hence, the resulting devices are limited to a planar element distribution as encountered, e.g., in edge emitting lasers.

OBJECTS AND ADVANTAGES

It is a primary object of the present invention to apply the technique of Selective Area Epitaxy (SAE) to vertical optical cavities. In particular, it is an object of the invention to provide vertical cavity surface emitting lasers (VCSEL) and Vertical Cavity Detectors (VCDET) with varying emission and absorption wavelengths by using SAE.

It is a further object of the invention to provide for simple adjustment of the band gap of Quantum Well regions (QWs) and of the Fabry-Perot distance between reflectors in such vertical cavity devices.

It is an additional object of the invention to ensure that the method of making the vertical optical cavity devices is simple and cost-efficient.

Yet another object of the invention is to ensure that vertical optical cavity devices can be grown monolithically and as arrays of elements.

Further objects and advantages will become apparent upon reading the specification.

SUMMARY

These objects and advantages are attained by a monolithic device with a vertical optical cavity built up along a vertical direction. The device has a bottom Distributed Bragg Reflector (DBR) made up of a number of bottom reflectors or alternating $\lambda/4$ layers. A Quantum Well (QW) region consisting of least one active layer is grown on top of the bottom DBR by using a Selective Area Epitaxy (SAE) mask or growing pattern. To ensure proper SAE growth of the QW the mask is made of a dielectric, a nitride or an oxide. Depending on the SAE conditions, the QW region can have one or more strained QWs. Additionally, the active layer or layers exhibit a variation in at least one physical parameter in a horizontal plane, i.e., in a plane perpendicular to the vertical direction. A top DBR consisting of a number of top reflectors is deposited on top of the QW region. A spacer is also deposited adjacent the QW region, e.g., below and/or above the QW region. The spacer can exhibit a variation in its surface curvature or it can have a varying thickness in the horizontal plane. The spacer is preferably also grown by SAE.

The device of the invention has a Fabry-Perot distance which is defined along the vertical direction between the bottom DBR and

the top DBR. This Fabry-Perot distance also varies depending on the position in the horizontal plane. For example, the Fabry-Perot distance varies due to varying thickness of the QW or of the spacer.

The varying physical parameter of the active layers is either their surface curvature and/or the band gap. Both of these parameters are regulated by SAE. The band gap is preferably adjusted by altering the relative concentration of materials or elements of the active layer in accordance with SAE.

The SAE mask in the simplest case includes two stripes separated by a gap in which the QW and the spacer are grown. The mask can also be selected from many shapes such as circular stripes, semi-circular stripes, wedge stripes and elliptical stripes as required. The mask shapes are tailored to control thickness and relative concentration of constituent materials of the active layers as well as polarization of the radiation supported by the optical cavity.

It is also preferable that the active layers have a first index of refraction and a first top reflector adjacent to the active region have a second index of refraction either larger or smaller that the first index of refraction. This difference in indices can be used for lensing, guiding or anti-guiding of electromagnetic radiation within the cavity. For better performance, the active layers should exhibit a predetermined surface curvature.

In a preferred embodiment the QW has a number of active layers and the surface curvature of each active layer is controlled. For example, the curvature of the bottom active layer can exhibit the largest bow and the curvature of the top active layer can have the least bow.

The vertical cavity device according to the invention can be used as a Vertical Cavity Surface Emitting Laser (VCSEL) or a Vertical Cavity Detector (VCDET). In the first case a current supply is provided for inducing the active layers to emit electromagnetic radiation. In the second case a suitable circuit is provided to

render an absorbing layer sensitive to incident electromagnetic radiation when absorbed.

The method of the invention permits one to construct vertical optical cavities by appropriately tailoring the SAE conditions. Further details and an explanation of the invention are contained in the detailed specification with reference to the appended drawing figures.

DESCRIPTION OF THE FIGURES

Fig. **1** is a cross sectional view illustrating some fundamental aspects of growth by Selective Area Epitaxy (SAE).

Fig. **2** is a cross sectional view showing an active layer grown by SAE.

Fig. **3** is a cross sectional view showing a number of active layers and a spacer grown by SAE.

Fig. **4A-F** are isometric views illustrating a preferred process of making a vertical optical cavity.

Fig. **5** is a cross sectional view showing the vertical optical cavity made by the preferred process.

Fig. **6** is a cross sectional view of a vertical optical cavity device used as a Vertical Cavity Detector (VCDET).

Fig. **7** is an isometric view of a general SAE mask.

Fig. **8A-E** are plan views of particular SAE masks.

Fig. **9A-C** are plan views of SAE masks for active layers with polarization control.

Fig. **10** is a plot of Quantum Well gain position and Fabry-Perot position of a Vertical Cavity Surface Emitting Laser (VCSEL) made with the aid of SAE according to the invention.

DETAILED DESCRIPTION

The vertical optical cavity devices of the present invention and the steps required to grow them rely on the use of the known technique of Selective Area Epitaxy (SAE). Fig. 1 illustrates the most relevant aspects of SAE when performing epitaxial growth by metal-organic chemical vapor deposition (MOCVD), molecular beam epitaxy (MBE) or metal organic molecular beam epitaxy (MOMBE) on a substrate **10**, e.g., a GaAs substrate.

A growing pattern or an SAE mask **12** with an edge **14** is deposited on top of substrate **10**. The material of mask **12** is a dielectric, a nitride, an oxide or any other suitable material which does not support epitaxial growth of a deposited material **16**. Thus, rather than growing on mask **12** precursors of material **16**, e.g., tri-methyl-Ga, migrates to the surface of substrate **10**. Hence, the growth of material **16** on substrate **10** is enhanced, especially near edge **14**. This is evidenced by the decreasing thickness of material **16** with increasing distance from edge **14**.

In addition to the decreasing thickness of material **16** away from edge **14**, individual components **18A**, **18B** and **18C** of material **16**, in this case In, Ga and As have different diffusion lengths. For illustration purposes, in Fig. 1 component **18A**, or Ga and component **18B**, or In are designated by circles and squares. A diffusion length DL_1 of Ga is smaller than a diffusion length DL_2 of In. Hence, the relative concentrations of Ga and In vary with distance from edge **14**.

SAE growth of material **16** also affects a surface **20** of the grown material. In particular, surface **20** has a natural bow or curvature due to SAE. The curvature is generally concave and results from the above-described effects of decreasing epitaxial growth with increasing distance from edge **14** and varying diffusion lengths of components **18A**, **18B**.

The basics of applying SAE to growing vertical optical cavities are illustrated in Figs. 2-3. In Fig. 2 an active layer **30** grown by SAE on a bottom Distributed Bragg Reflector **32** consists of

alternating reflectors or λ/4 layers **34**. A mask **36** has a gap **38** within which active layer **30** is deposited. Active layer **30** has a concave surface **39**. Fig. 3 shows the result of removing mask **36** and growing additional layers **40**, in this case a spacer **42** and a top DBR **44** consisting of λ/4 layers **46** on top of active layer **30** without SAE. The surface curvature of each successive layer is smaller and the curvature of the topmost layer **46** of top DBR is approximately zero.

The isometric views of Figs. 4A-F show how the above-described principles of SAE growth are used to produce a preferred vertical optical cavity device **100** (see Fig. 4F). Device **100** is grown along a vertical direction or the z-direction. First, as shown in Fig. 4A, a bottom DBR **50** consisting of bottom reflectors or λ/4 layers **52** is grown by standard epitaxy techniques such as MOCVD or MBE. Layers **52** are actually layer pairs **52A**, **52B**, e.g., GaAs/AlAs pairs. The number of GaAs/AlAs layer pairs depends on the desired reflectivity and will be determined by the designer based on well-known principles. For example, if device **100** is to be used as a Vertical Cavity Surface Emitting Laser (VCSEL) the number of GaAs/AlAs layer pairs can range between 30 and 40 or more to ensure sufficiently high reflectivity for DBR **50** to function as a high reflector.

A spacer **54** is also grown on bottom DBR **50**. In this case spacer **54** is made up of two layers **56**, **58** consisting of, for example, $Al_{0.2}Ga_{0.8}As$ and GaAs. A person of average skill in the art will be able to determine the required thickness and composition of spacer **54**.

In the next step the surface of layer **58** is patterned to produce an SAE mask **60**. As illustrated in Fig. 4B, mask **60** consists of two stripes **62**, **64** with a gap **66** between them. Stripes **62**, **64** are made of silicon nitride and their width, w, tapers down along the y-direction. Meanwhile, the width, d, of gap **66** remains constant. After the patterning step the surface of layer **58** and stripes **62**, **64** are cleaned for regrowth.

For any mask made up of two stripes the SAE enhancement factor E_x for material x is characterized by the following linear relationship:

$$E_x \propto \frac{w}{d}.$$

Therefore, in the case of mask **60** the Ga and In enhancement factors, E_{Ga} and E_{In}, both decrease along the y-direction.

During the next step a layer **68** of GaAs is grown in gap **66** by SAE. The result is shown in Fig. 4C. Layer **68** has a curved surface **69** due to SAE growth conditions explained above and the thickness of layer **68** tapers off along the y-direction because of reduced SAE enhancement.

Subsequently, as shown in Fig. 4D, three Quantum Wells (QWs) or active layers **70** are grown by SAE in gap **66** between stripes **62**, **64**. Typically, thin interlayers (not shown) are also grown between Qws **70** as required. Active layers **70** with any eventual interlayers make up a Quantum Well (QW) region **72**. Active layers **70** are made of an active material or lasing medium. For example, a suitable lasing material is $In_{0.17}Ga_{0.83}As$. Of course, QW region **72** may also be made up of more active layers like layer **70** thus producing a larger stack of QWs or, alternatively, just one active layer **70**.

Since the diffusion length of Ga is less than the diffusion length of In the surfaces of active layers **70** are curved and the relative concentrations of In and Ga vary depending on the distance from stripes **62**, **64** along the x-direction. Also, the overall thickness of active layers varies in the y-direction because of decreasing SAE enhancement. Thus, two physical parameters, the relative concentration of In and Ga and the thickness of active layers **70** vary in a horizontal plane, specifically the x-y plane.

These two physical parameters influence the local band gap of active layers **70** at all locations in the x-y plane. In other words, the gain position of device **100** is controlled by the thickness and composition of the QW region **72** and specifically of active layers **70**. Both of these physical parameters are a

function of SAE enhancement as discussed above. Care has to be taken to ensure that the SAE enhancement factor E_x is not too large such that the thickness and composition of active layers **70** and layer **68** do not exceed a critical thickness. Otherwise, the crystal lattice will relax and defects will be generated which will prevent the finished device from functioning. A person of average skill in the art is familiar with this problem and will be able to ensure that the critical thickness is not exceeded.

Active layers **70** are covered by a layer **74** of inert material, e.g., GaAs. Although in Fig. 4D layer **74** is grown with stripes **62** and **64** present and therefore benefits from SAE growth it is also possible to remove stripes **62** and **64** at any point during the growth of layer **74**. The remainder of layer **74** can then be grown with the normal MOCVD technique. A total thickness, t, indicates the thickness of growth obtained with the aid of SAE.

The structure remaining after the removal of stripes **62**, **64** of mask **60** is shown in Fig. 4E. This removal is performed according to well-known methods, such as a buffered-oxide etch (BOE). The decrease in thickness of inert layer **68** and of active layers **70** of QW region **72** along the y-direction is clearly visible. The natural bow or concave curvature due to SAE growth is present as well, though not explicitly shown in this drawing (see Fig. 2). The curvature translates into thickness variation along the x-axis. In particular, the thickness of active layers **70** is smallest exactly half-way between stripes **62**, **64** and increases gradually as one moves closer to stripes **62**, **64**.

Because of the variation in the thickness of active layers **70** of QW region **72** and change in the relative concentration of In and Ga in active layers **70** the band gap of active layers **70** varies in the x-y plane. The variation along the y-direction is primarily due to the decreasing thickness of layers **70** and variation in Ga and In concentration. The variation along the x-axis is primarily due to the change in surface curvature of layers **70** and also due to the change in relative concentration of In and Ga in layers **68**, **70** and **74**.

The last steps of the method involves growing a top spacer **75**, which may consist of two separate layers (not shown), e.g., GaAs and $Al_{0.2}Ga_{0.8}As$, and a top DBR **76**, as illustrated in Figs. 4F and 5. Like bottom DBR **50**, top DBR **76** is made up of top reflectors or pairs of layers **78A**, **78B**. These can be tailored like and have the same composition as layers **52A**, **52B**. The reflectivity of top DBR **76** is selected based on whether device **100** is to be a VCSEL or a VCDET. In the former case the number of layers **78A**, **78B** should be smaller than the number of layers **52A**, **52B** to ensure a lower reflectivity of top DBR **76** such that it can function as an output coupler.

The very final step involves processing a top surface **80** of the topmost layer **78B** of top DBR **76** to produce an array **83** of output windows or facets **81** along the y-direction. Because of the decreasing thickness of layer **68**, QWs **70** and top spacer **75** a Fabry-Perot distance **82** between bottom DBR **50** and top DBR **76**, as defined in the corresponding cross sectional view of Fig. 5, decreases along the y-direction. As is well-known, distance **82** determines the length of a Fabry-Perot type lasing cavity **84** which, in turn, determines what wavelength λ of electromagnetic radiation **86** is permitted to oscillate inside cavity **84**. Clearly, the wavelength λ of radiation **86** permitted by Fabry-Perot distance **82** decreases along the y-direction.

Meanwhile, the gain position of QWs **70** also varies along the y-direction, as described above. In particular, the gain position decreases along the y-direction such that QWs **70** produce gain at the wavelength λ dictated by Fabry-Perot distance **82** at each point along the y-direction. Hence, each window **81** of array **83** emits radiation **86** at a different wavelength $\lambda_1, \lambda_2, \ldots \lambda_n$. In this case device **100** is a multiple-wavelength VCSEL. Bottom DBR **50** is the high reflector while top DBR **76** is the output coupler.

Fig. 6 illustrates a device **101** essentially analogous to device **100** designed to function as a multiple wavelength VCDET **101** or an array of VCDETs. The method of making device **101** is also analogous to the method of making device **100**. In this case,

however, top DBR **76** has approximately the same reflectivity as bottom DBR **50**. In addition, a bottom p-i-n absorbing region **88** is provided to absorb incident radiation **87** whose λ matches the resonant λ determined by Fabry-Perot distance **82**. Radiation **87** of a wavelength λ to be detected is admitted into VCDET **101** through surface **80**. Instead of QW region **72**, passive filter layers **71** form a filter spacer which exhibits thickness, curvature and composition variations in the x-y plane due to SAE. A standard detection circuit (not shown) is also provided to detect the electrical pulses generated in layer **88** as radiation **87** is absorbed.

Since Fabry-Perot distance **82** varies in the x-y plane, and specifically along the y-direction, the wavelength λ of radiation **87** which can be detected by VCDET **101** also varies along the y-direction. Given that same mask **60** is used for making VCDET **101** as VCSEL **100**, then the wavelength λ of detectable radiation **87** will decrease along the y-direction. Thus, with a map of λ or Fabry-Perot distance **82** as a function of y position VCDET **101** can be used to detect an entire bandwidth of radiation **87**. Furthermore, VCDET **101** can have input windows or facets **81** just like VCSEL **100** or have one continuous facet for continuous wavelength detection.

From the above description it will be apparent to a person of average skill in the art that SAE mask **60**, and particularly the geometry of gap **66** is crucial to tailoring the band gap and Fabry-Perot distance **82**. A general mask **90** is shown in Fig. 7. Mask **90** has two stripes **92**, **94** defining a gap **96** between them. The width of stripe **92** varies along length L and is represented by a function f1(L). Analogously, the width of stripe **94** varies with length L and is represented by f2(L). In the present case the width variations of stripes **92** and **94** are symmetric but they do not have to be. Also, the width of gap **96** is constant, but it can vary. Once again, the width w of stripes **92**, **94** and the width d of gap **96** are dictated by the desired SAE enhancement factor E_x according to the relation:

$$E_x \propto \frac{w}{d}.$$

Based on this information, a person familiar with SAE will know how to select the proper functions f1(L) and f2(L) to produce proper growth enhancement in gap **96** to produce active layers with the desired concentration variation along the x- and y-directions in the x-y plane, surface curvature and overall thickness variation.

Figs. 8A-E show some particularly useful mask shapes. For example, a mask **102** shown in Fig. 8A is similar to mask **60** used for making devices **100** and **101**. It consists of two stripes **104**, **106** defining a constant width gap **108**. Stripes **104**, **106** widen and enhance SAE growth in gap **108** more at their wide ends than at their narrow ends. Fig. 8B shows a mask **110** consisting of triangular stripes **112** and **114** with a constant width gap **116**. Mask **110** enhances SAE growth more at the wide ends of triangles **112** and **114** than at their corners. Fig. 8C illustrates a mask **120** with a gap **126** defined between two step-graded triangular stripes **122** and **124**. The SAE growth enhancement factor for mask **120** will be constant at each step and undergo a discontinuous increase towards the wide end of stripes **122** and **124** at each step. A mask **130** of Fig. 7D has two stripes **132**, **134** which do not vary in width, but are set aslant to each other such that they define a gap **136** of varying width. Mask **130** is similar to mask **60** discussed above.

Mask **120** is useful for large-scale manufacturing because it is more tolerant to misalignment of output facets in the final device. This is due to the fact that the SAE enhancement varies step-wise and so do the Fabry-Perot distance and QW gain position. On the other hand, the steps of mask **120** have to be very precisely dimensioned. In contrast, masks **102**, **110** and **130** exhibit continuous variation in SAE enhancement, Fabry-Perot distance and QW gain position. They thus provide for continuous adjustments in the position of the output facets such that Fabry-Perot distances determining the desired wavelengths λ_1, λ_2, ...λ_n are aligned with the desired output facets.

Fig. 8E illustrates four circular masks **140**, **142**, **144** and **146** which are essentially circular stripes having central openings **150**, **152**, **154** and **156** corresponding to the gap where SAE growth is enhanced. The widths of masks **140**, **142**, **144** and **146** vary progressively from thin to thick while central openings **150**, **152**, **154** and **156** remain the same. Clearly, SAE growth is enhanced least by mask **140** in opening **150** and most by mask **146** in opening **156**. To a first approximation, the SAE enhancement factor E_x for circular masks is given by the following relation:

$$E_X \propto \frac{MA}{OA},$$

where MA is the surface area of the mask and OA is the area of the opening.

According to an additional aspect of the invention, the natural curvature due to SAE growth is further used to control the polarization of emitted radiation, e.g., radiation **86** in device **100**. This is done by introducing an asymmetry in the SAE grown layers **68**, **70** and, as the case may be in layer **74**, by using an asymmetric mask. An asymmetric mask produces a strain and/or thickness difference along one crystal orientation of the layers grown by SAE. Suitable asymmetric SAE mask patterns include trapezoids of Fig. 8D and masks **160**, **170** and **180** shown in Figs. 9A-C.

When using any of the above asymmetric masks with InGaAs quantum wells a strain asymmetry will additionally be introduced due to the differential growth rate enhancement of In and Ga as discussed above. Hence, SAE growth in this case will produce differential strain along different directions (e.g., along the major and minor axes of mask **160**).

The method of the invention also permits to produce devices with built-in positive and negative lensing and index guiding and anti-guiding. Referring back to Fig. 3, when active layer **30** is made of a material which a larger refractive index than the effective index of layers **40**, and especially the adjacent layer **42**, then electromagnetic radiation will experience a diverging lens effect

due to the curvature of surface **39** and the index difference. Alternatively, when the index of active layer **30** is smaller than that of layers **40**, and especially of layer **42**, then the radiation will experience a converging lens effect. The lensing effect is especially large when the curvature of surface **39** is significant and the index difference is large. For example, by making layer **30** according to SAE a thickness difference of 4% can be achieved between the center of layer **30** and its edges while producing a viable quantum well.

Additionally, the positive and negative lensing effects cause index guiding and anti-guiding according to well-known principles. Hence, the method of the invention can be used to enhance single-mode operation in the devices it produces in the small index guiding and any index anti-guiding areas.

EXAMPLE

The following example merely serves to illustrate a particular embodiment of the invention and is not intended as a limitation. A practical VCSEL array capable of generating output radiation with λ ranging from 930-980 nm is produced using a mask consisting of two closely spaced trapezoidal strips (see Fig. 8A). First, one grows a bottom DBR consisting of 35 pairs of GaAs/AlAs distributed Bragg reflectors and 52 nm of $Al_{0.2}Ga_{0.8}As$ and 24.8 nm of GaAs with MOCVD or MBE in an appropriate chamber.

The wafer is then patterned with 100 nm silicon nitride to produce the SAE mask as shown in Fig. 8B. The width w of the mask varies from 0 to 100 μm and it is 1,000 Angstroms thick. The wafer is cleaned for regrowth using HCl and reloaded into the chamber. During the SAE growth one produces a 26.5 nm layer of GaAs covered by three 4.2 nm $In_{0.17}Ga_{0.83}As$ quantum wells with 10 nm separation or intermediate layers and another 26.5 nm thick layer of GaAs.

At this point the wafer is removed from the chamber and the silicon nitride is removed with BOE. The wafer is then again re-loaded into the chamber to re-grow 24.8 nm of GaAs without SAE enhancement, 52 nm of $Al_{0.2}Ga_{0.8}As$ and 26 pairs of $GaAs/Al_{0.7}Ga_{0.3}As$

DBR. The total thickness t of material grown with SAE is preferably t=855 nm.

During the final step the VCSEL array is fabricated along the center line of the SAE mask. The finished device is similar to device **100** shown in Fig. 4F.

The performance of the finished VCSEL array is characterized by the plot in Fig. 10 which graphs the QW gain position and the Fabry-Perot position as a function of width (w) of the SAE strips. The plot includes data point for the VCSEL grown as described with the preferred SAE growth thickness t=85.5 nm and two other thicknesses--t=65.3 nm and t=112.7 nm--for comparison purposes. With the preferred thickness the Fabry-Perot distances are matched with the gain position and thus proper functioning of the VCSEL array is guaranteed.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. For example, the method of the invention can be used with InGaP, InGaAs, InGaAsP and AlGaAs material systems to produce devices according to the invention. It should be noted that growing device according to the invention with with AlGaAs the QWs will automatically be pre-strained.

In view of the above, the scope of the invention should be determined by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1. A monolithic vertical optical cavity extending along a vertical direction and comprising:
   a) a bottom Distributed Bragg Reflector having a plurality of bottom reflectors;
   b) a Quantum Well region grown on top of said bottom Distributed Bragg Reflector using a Selective Area Epitaxy mask, said Quantum Well region comprising at least one active layer having at least one physical parameter exhibiting a variation in a horizontal plane;
   c) a top Distributed Bragg Reflector deposited on top of said Quantum Well region and having a plurality of top reflectors;

   where a Fabry-Perot distance defined along said vertical direction between said bottom Distributed Bragg Reflector and said top Distributed Bragg Reflector varies in said horizontal plane.

2. The monolithic vertical optical cavity of claim 1 wherein said at least one physical parameter is selected from parameter consisting of surface curvature of said at least one active layer and band gap of said at least one active layer.

3. The monolithic vertical optical cavity of claim 1 wherein said Selective Area Epitaxy mask comprises two stripes.

4. The monolithic vertical optical cavity of claim 1 wherein said Selective Area Epitaxy mask comprises shapes selected from the group consisting of circular stripes, semi-circular stripes, wedge stripes and elliptical stripes.

5. The monolithic vertical optical cavity of claim 1 wherein said Selective Area Epitaxy mask comprises a material selected from the group consisting of dielectrics, nitrides and oxides.

6. The monolithic vertical optical cavity of claim 1 wherein said active layer has a first index of refraction and a first top reflector adjacent said active region has a second index of refraction larger than said first index of refraction.

7. The monolithic vertical optical cavity of claim 6 wherein said at least one physical parameter comprises a surface curvature of said active layer.

8. The monolithic vertical optical cavity of claim 1 wherein said active region has a first index of refraction and a first top reflector adjacent said active layer has a second index of refraction smaller than said first index of refraction.

9. The monolithic vertical optical cavity of claim 8 wherein said at least one physical parameter comprises a surface curvature of said active layer.

10. The monolithic vertical optical cavity of claim 1 wherein said Quantum Well region has a varying thickness in said horizontal plane such that said Fabry-Perot distance varies in said horizontal plane.

11. The monolithic vertical optical cavity of claim 1 further comprising a spacer deposited adjacent said at least one active region.

12. The monolithic vertical optical cavity of claim 11 wherein said spacer has a varying thickness in said horizontal plane.

13. The monolithic vertical optical cavity of claim 11 wherein said spacer has a varying curvature.

14. The monolithic vertical optical cavity of claim 11 wherein at least a portion of said spacer is grown using said Selective Area Epitaxy mask.

15. The monolithic vertical optical cavity of claim 1 wherein said at least one physical parameter is a band gap of said active layer and said variation is a variation in relative concentration of components comprising said at least one active layer.

16. The monolithic vertical optical cavity of claim 1 wherein said Quantum Well region is a strained Quantum Well region.

17. The monolithic vertical optical cavity of claim 1 wherein said at least one active layer comprises a number n of active layers.

18. The monolithic vertical optical cavity of claim 17 wherein said at least one physical parameter is a surface curvature of each of said n active layers.

19. The monolithic vertical optical cavity of claim 18 wherein said surface curvature is different in each of said n active layers.

20. A method of making a monolithic vertical optical cavity extending along a vertical direction comprising the following steps:

a) depositing a plurality of bottom reflectors to produce a bottom Distributed Bragg Reflector;

b) producing a Selective Area Epitaxy mask on top of said bottom Distributed Bragg Reflector;

c) using said Selective Area Epitaxy mask for growing a Quantum Well region on top of said bottom Distributed Bragg Reflector, said Quantum Well comprising at least one active layer having at least one physical parameter exhibiting a variation in a horizontal plane;

d) depositing a plurality of top reflectors to produce a top Distributed Bragg Reflector, whereby a Fabry-Perot distance is defined along said vertical direction between said bottom Distributed Bragg Reflector and said top

Distributed Bragg Reflector and said Fabry-Perot distance varies in said horizontal plane.

21. The method of claim 20 wherein said at least one physical parameter is a surface curvature of said at least one active layer and said method further comprises the step of determining said surface curvature.

22. The method of claim 21 wherein the step of determining said curvature is performed by varying said Selective Area Epitaxy mask.

23. The method of claim 20 wherein said at least one physical parameter is a band gap of said at least one active layer and said method further comprises the step of altering said band gap.

24. The method of claim 23 wherein said step of altering said band gap is performed by altering a relative concentration of components comprising said at least one active layer.

25. The method of claim 20 further comprising the step of growing a spacer adjacent said Quantum Well region.

26. A vertical cavity detector with a monolithic vertical optical cavity extending along a vertical direction said detector comprising:

a) a bottom Distributed Bragg Reflector having a plurality of bottom reflectors;

b) a Quantum Well region grown on top of said bottom Distributed Bragg Reflector using a Selective Area Epitaxy mask, said Quantum Well region comprising at least one layer having at least one physical parameter exhibiting a variation in a horizontal plane;

c) a top Distributed Bragg Reflector deposited on top of said Quantum Well region and having a plurality of top reflectors;

where a Fabry-Perot distance defined along said vertical direction between said bottom Distributed Bragg Reflector and said top Distributed Bragg Reflector varies in said horizontal plane.

27. The vertical cavity detector of claim 1 wherein said Quantum well region comprises at least one active layer capable of lasing.

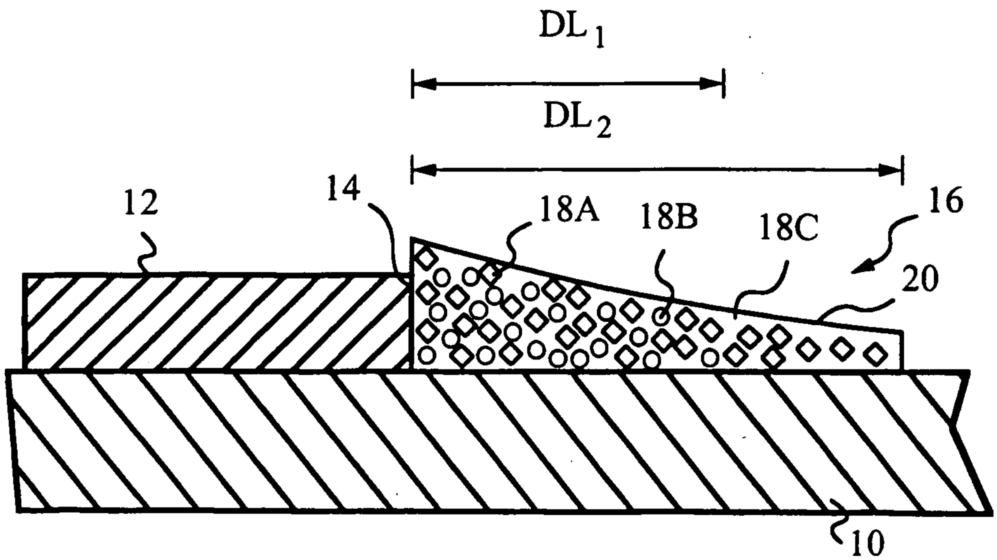


FIG. 1

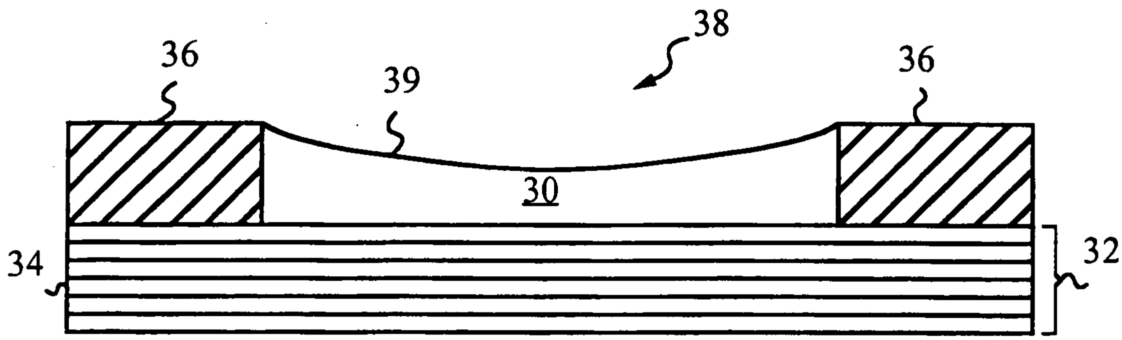


FIG. 2

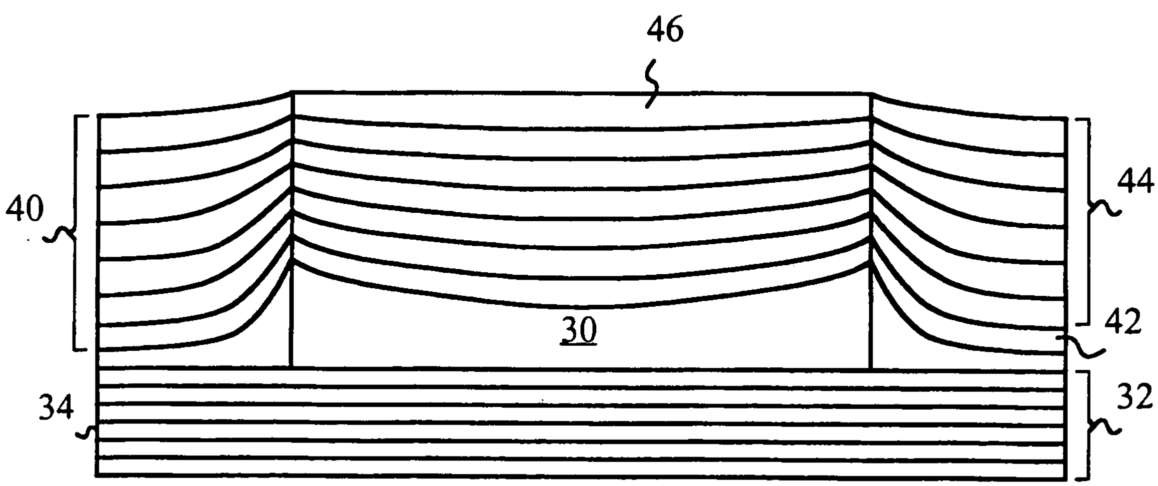


FIG. 3

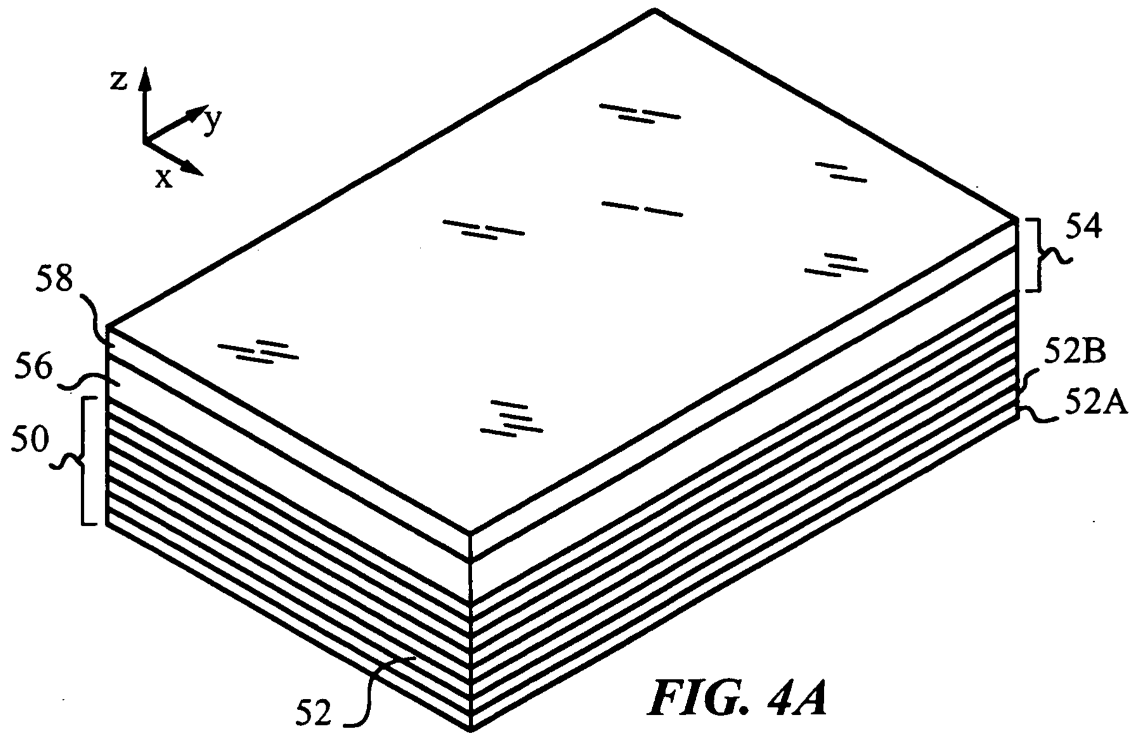


FIG. 4A

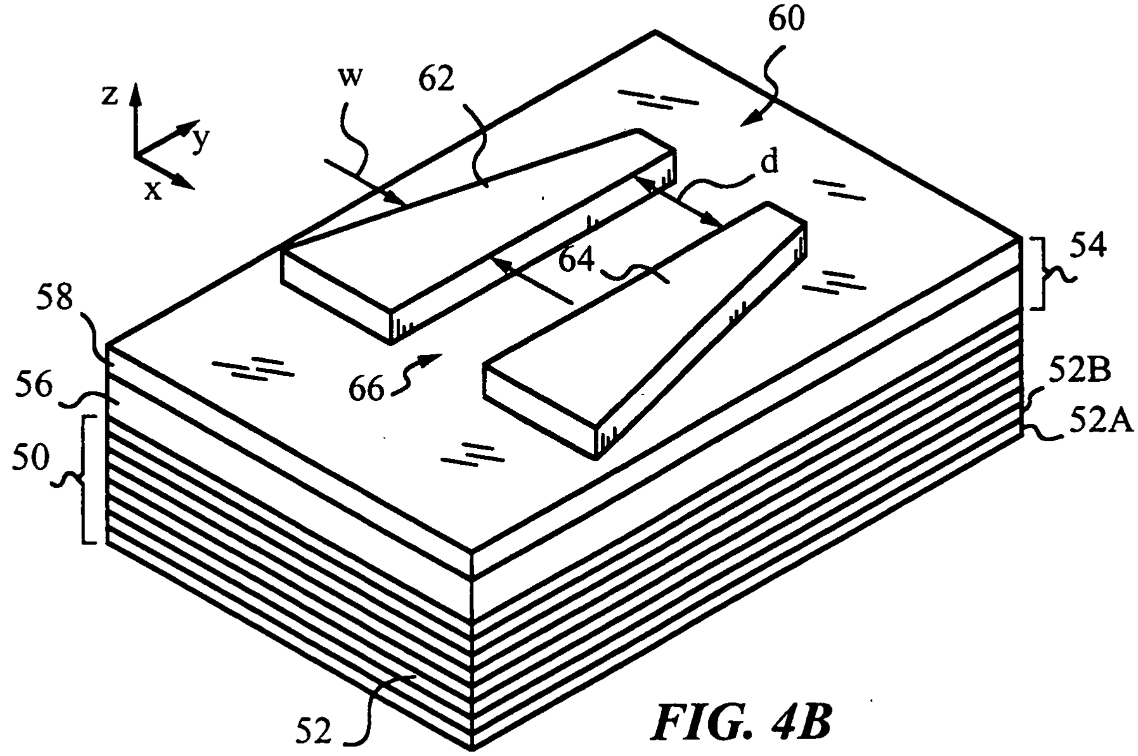
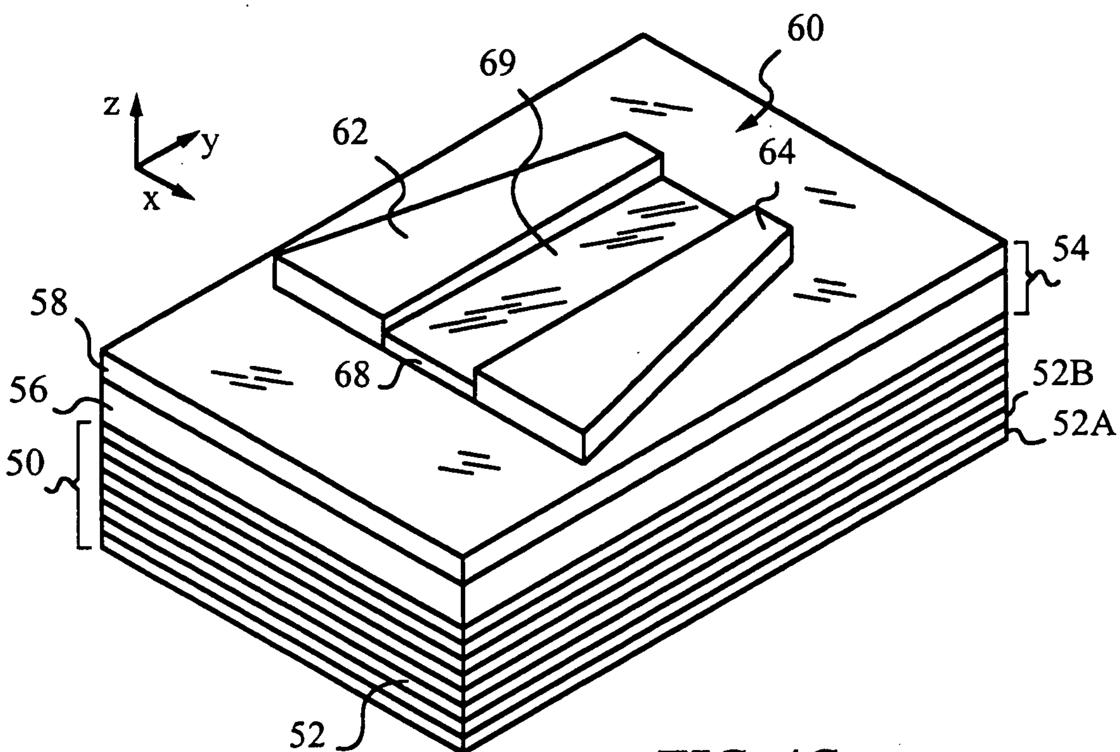


FIG. 4B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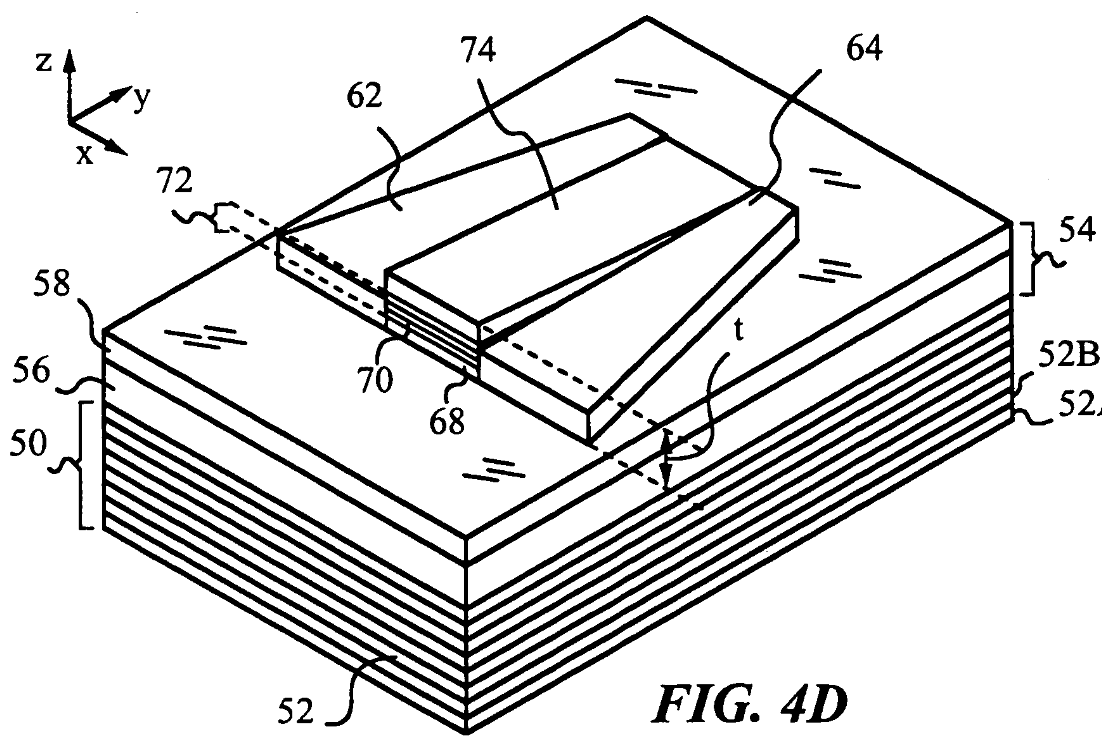
62
64
z
y
x
54
58
68
56
52B
52A
50
52

FIG. 4C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x
72
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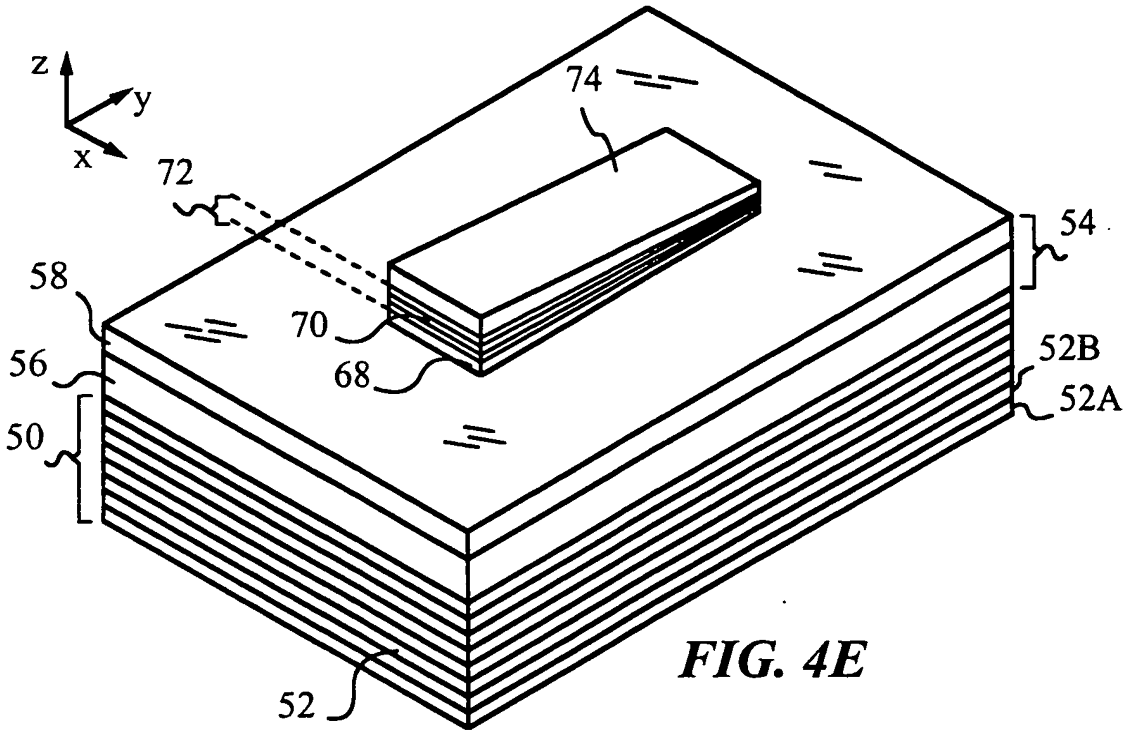
58
70
t
56
68
52B
52A
50
52

FIG. 4D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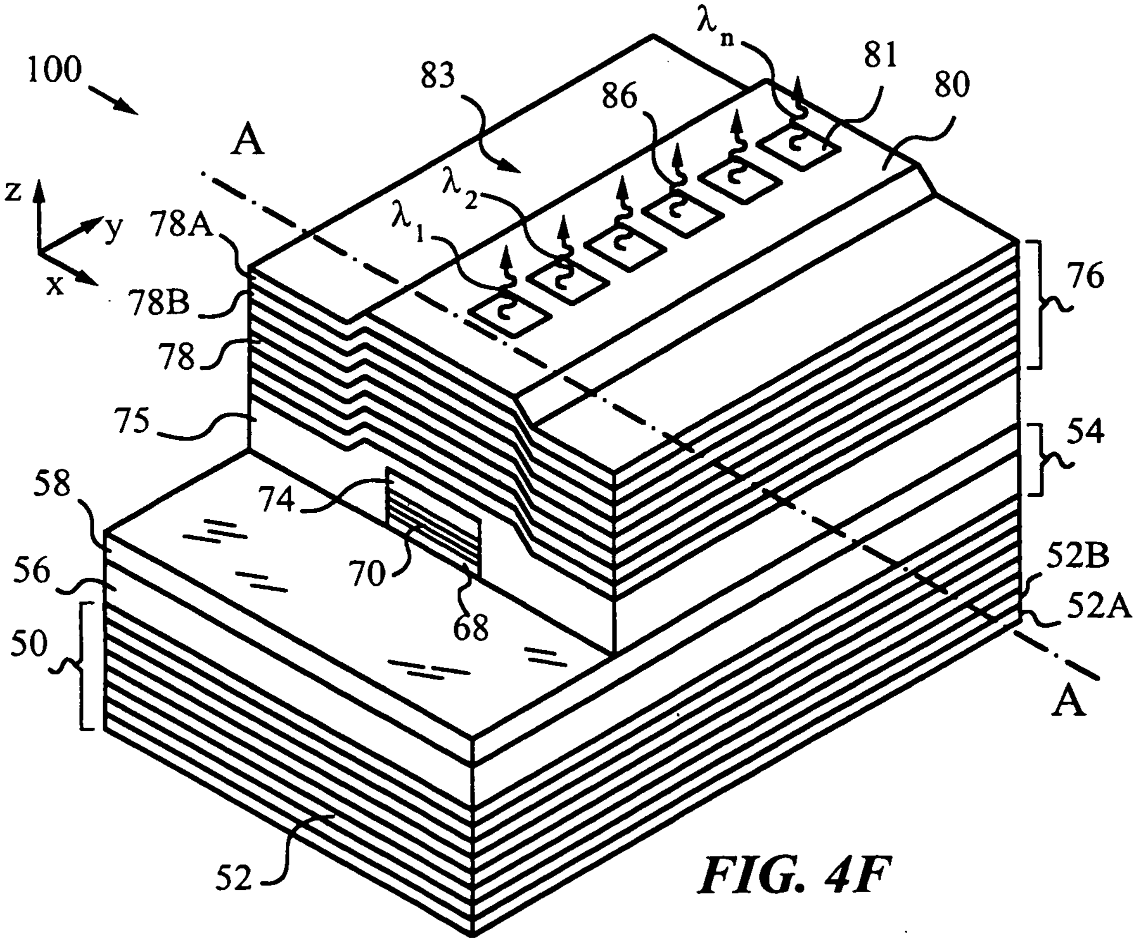
56
68
52B
52A
50
52

FIG. 4E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λn
81
80
86
A
λ2
z
y
78A
λ1
76
x
78B
78
75
54
58
74
56
70
52B
68
52A
50
A
52

FIG. 4F

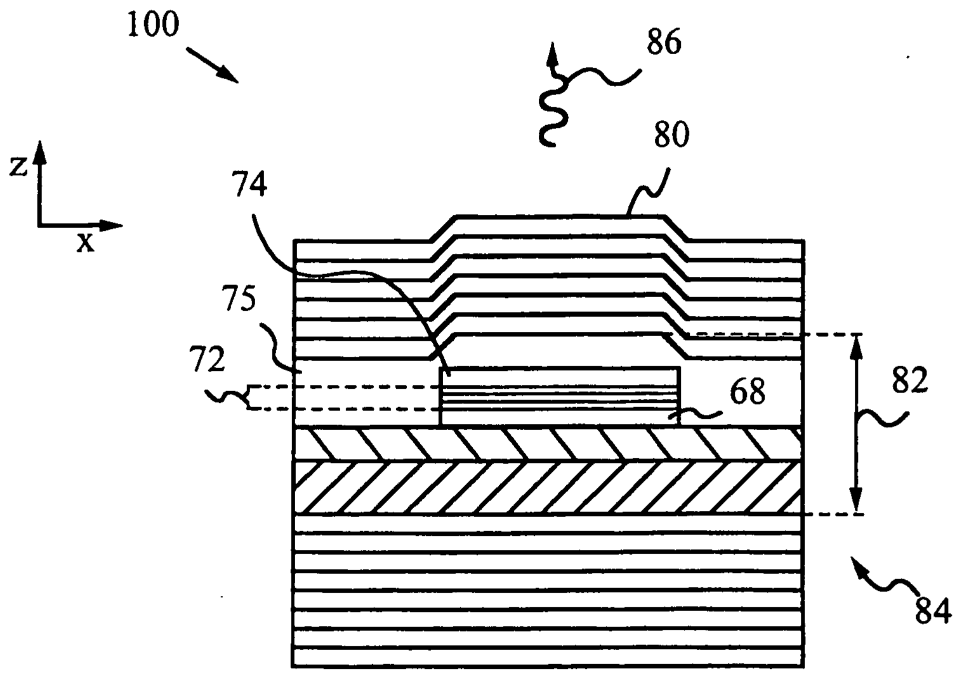

FIG. 5

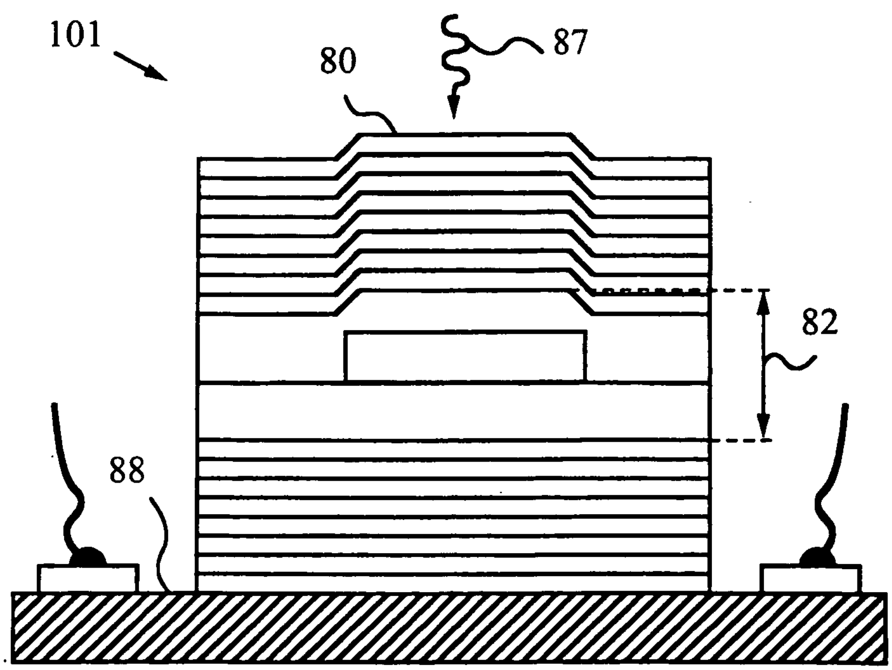

FIG. 6

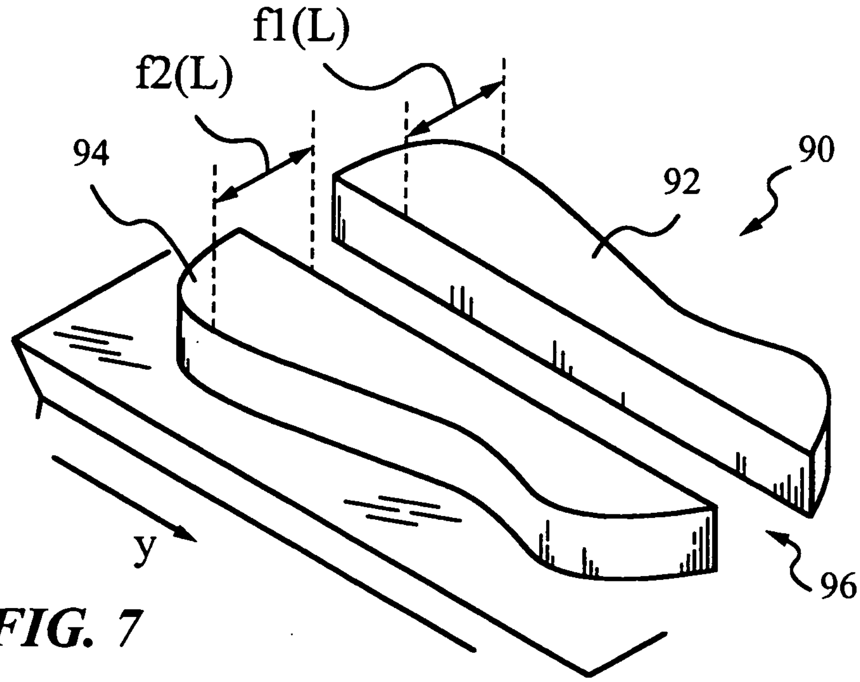

FIG. 7

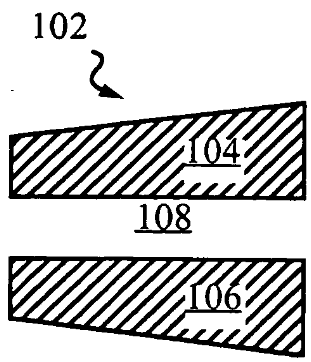

FIG. 8A

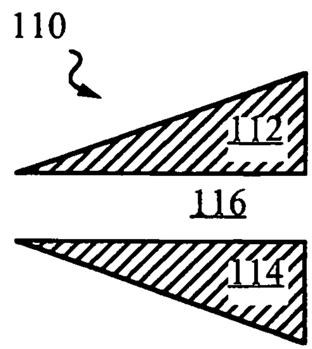

FIG. 8B

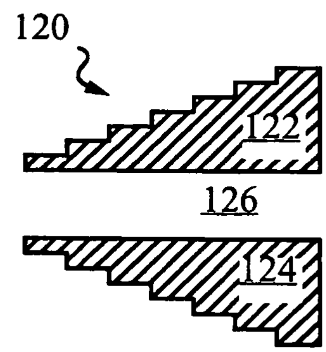

FIG. 8C

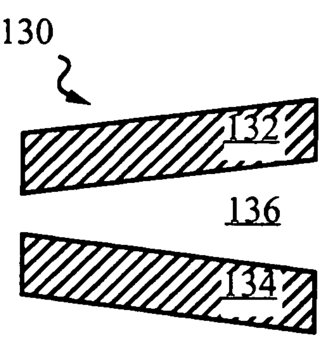

FIG. 8D

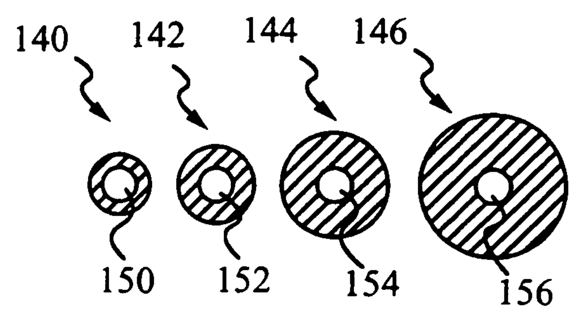

FIG. 8E

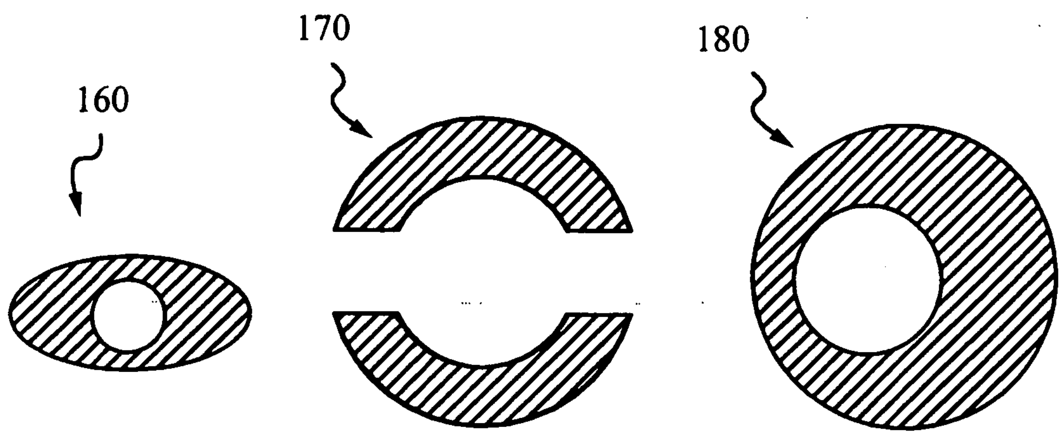

FIG. 9A FIG. 9B FIG. 9C

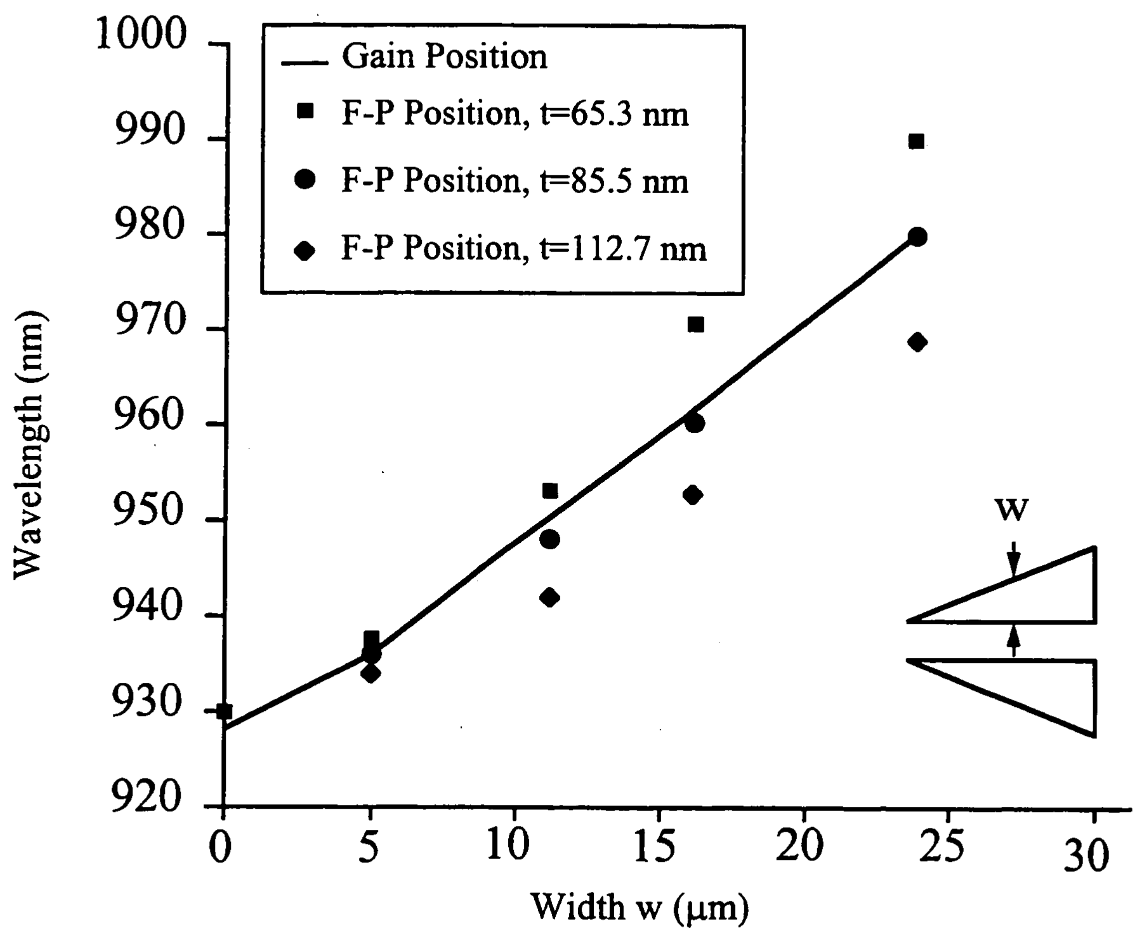

FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/03991

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H01S 3/19
US CL :372/96, 45, 46, 50
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 372/96, 45, 46, 50

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS, DIALOG

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,812,577 A (DAWSON ET AL) 22 September 1998 (22/09/98), see entire document, especially Figure 2.	1-27
A	US 5,677,924 A (BESTWICK) 14 October 1997 (14/10/97), see entire document, especially Figure 5.	1-27
A	US 5,446,752 A (ACKLEY ET AL) 29 August 1995 (29/08/95), see entire document, especially Figure 3.	1-27

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 APRIL 1999	5 MAY 1999

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT	YISUN SONG